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G. H. Miller
Iowa State College

R. A. Lowry
Iowa State College

J. E. Osher
Iowa State College

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OPERATING CHARACTERISTICS OF A D.C. MAGNETIC ION SOURCE

by

G. H. Miller, R. A. Lowry, and J. E. Osher

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I. ABSTRACT

The operating characteristics of an ion source of the type described by Kistemaker and Dekker are given. The dependence of the total ion output on the ion source pressure, magnetic field, anode voltage, filament emission, and probe voltage is described. When hydrogen gas was used the ion source operated stably for pressures in the range of 1.5 to 2.5 microns of Hg producing maximum ion currents of 3 to 5 ma. Its gas consumption was relatively high (22.5 cc/hr, STP) and the proton percentage of the ion beam was of the order of 8%. The best focusing gave a beam diameter of 5 mm on a target 2 meters from the ion source. The filament lifetimes varied from 50 to more than 100 hours. The power consumption for ion beams of 3 ma or less was found to be about 0.15 watts/ua.

II. INTRODUCTION

During the last four years considerable work has been done at this laboratory on the construction of ion sources to be used to produce protons, deuterons, and other heavy ions for acceleration by the kevatron. It is the purpose of this report to summarize this work and to present significant results.

Some of the first work was done with a Zinn (1) type ion source. However, its construction was evidently faulty and consequently it failed to perform satisfactorily. Considerable effort was also spent on the construction of a Philips type (2) ion source, but its ion output was also erratic and insufficient. The first ion source used on the kevatron with any degree of success was one of the type described by Bailey, Drukey, and Oppenheimer (3). Ion currents as large as 2 ma were obtained with this ion source, but more reliable and stable operation produced ion beams of 1 ma or less. Contrary to Bailey's, etc., report, the proton percentage of the ion beam was found to be disappointingly low (of the order of 6%).

In an effort to obtain larger ion currents and with the hope of increasing the proton percentage, an ion source of the type described by Kistemaker and Dekker (4) was constructed. This report is chiefly concerned with the performance of this ion source. This type of ion source tends to increase the efficiency of ionization by causing the electrons to oscillate within a hollow anode by means of an axial magnetic field and a reflecting electrode at the end of the anode. Furthermore, by placing the filament between the anode and the exit hole the efficiency of extracting the ions from the plasma is increased. Kistemaker and Dekker reported very low operating pressures (0.04 to 0.5 microns of Hg) and a correspondingly low gas consumption. Space charge limited ion currents of 5 to 10 ma were reported but no analysis of the composition of their ion beams was given.

More recently Cornelius and Farwell (5) described the performance of a similar ion source. They reported operating pressures for H_2 of 1 to 2 microns of Hg with a gas consumption of 1.5 to 3 cc/hr, STP. They obtained resolved proton beams of 30 μ a and resolved He^+ beams of 70 μ a for H_2 and He gas, respectively. Their analysis of the unresolved hydrogen beam indicated a proton percentage of 5 to 9%.

This low proton percentage is consistent with the fact that metal surfaces have a large coefficient of recombination for H atoms. Most reports of high proton percentages (greater than 50%) have been for ion sources which had a pyrex or quartz envelope (6,7,8,9). These two materials have a much lower coefficient of recombination than do metal surfaces. Veenstra (10,11) reported a proton percentage of 50% from a magnetic ion source in which the metal electrodes operated at a red temperature and were insulated from the metal walls by a pyrex sleeve. Lorrain (12) reported an increase in the proton percentage of a metal ion source to 50% with the addition of 10% O_2 to the hydrogen. Both Lorrain (12) and Isoya (9) discussed the ionization processes which occur in the ion sources and gave as the most probable process for the production of protons as the double process:

$$H_2 + e^- \longrightarrow H + H + e^-$$

$$H + e^- \longrightarrow H^+ + 2e^-$$

The most probable process for the production of diatomic ions was given as:

$$H_2 + e^- \longrightarrow H_2^+ + 2e^-$$

The cross section for this process has a maximum at an electron energy of about 75 ev. The cross section for the dissociation step in the proton production has a maximum at about 15 volts and is about six times as large as the cross section for the process which produces diatomic ions.

III. DESCRIPTION OF THE ION SOURCE

The Kistemaker and Dekker type ion source is shown schematically in Figure 1. The anode F was a brass cylinder, 7/8 in. I.D. with a stainless steel extension R which had a 5/8 in. I.D. This extension could be raised and lowered to determine its optimum position relative to the bottom plate. The brass anode cylinder was soldered into the brass flange C which in turn was supported by three porcelain insulators D. The anode lead was brought through the glass-to-kovar seal A which was soldered into the top plate B. The gas inlet and the vacuum gauges were also connected to the ion source through the top plate. The magnet coil E was wound directly onto the outside of the ion source with 29 layers of 29 turns each of #12 magnet wire. This produced a magnetic field intensity on the axis at the center of the coil of about 85 oersteds per ampere of coil current and at the end of the anode extension of approximately 35 oersteds per ampere of coil current. The maximum coil current was limited to 10 amperes.

The filament G was supported by the two leads O which were attached to the plate P; one was soldered directly to it and the other extended through the glass-to-kovar seal N. Thus, the filament could be easily removed for replacement by removing the plate P. When fastening a new filament into place the filament assembly was held in a jig to assure that the filament would be centered with respect to the exit hole when reinserted into the ion source. With the above arrangement for supporting the filament, one side of it was ordinarily at the potential of the ion source case. However, it was found possible to insulate the filament by using a thick teflon gasket and enlarging the bolt holes in the plate P to permit textolite bushings to be used to insulate the bolts. The filaments were made of 20 mil tungsten wire and were in the form of either a $2\frac{1}{2}$ turn flat spiral ($\frac{1}{2}$ in. O.D., 1/8 in. I.D.) or a $2\frac{1}{2}$ turn helix (3/16 in. O.D., 1/8 in. I.D., and 1/8 in. long). Both types of filaments were tried at various distances from the anode.

The bottom plate J was made of iron and soldered to the iron flange Q. The diameter of the exit hole H was varied from 0.06 to 0.12 in. The probe I was made of stainless steel and threaded to facilitate adjusting the spacing between it and the exit hole. The diameter of the opening in the probe was varied from 0.12 to 0.25 in. The probe and the lower side of the bottom plate J were shaped in a manner to give good focusing as interpreted from Pierce's work (13). The probe assembly was supported from the steel flange M which was insulated by the mycalex rings K. Bolts with fluorothene bushings L were used to assemble the ion source and fasten it onto the accelerator tube. All gaskets in the ion source were of teflon.

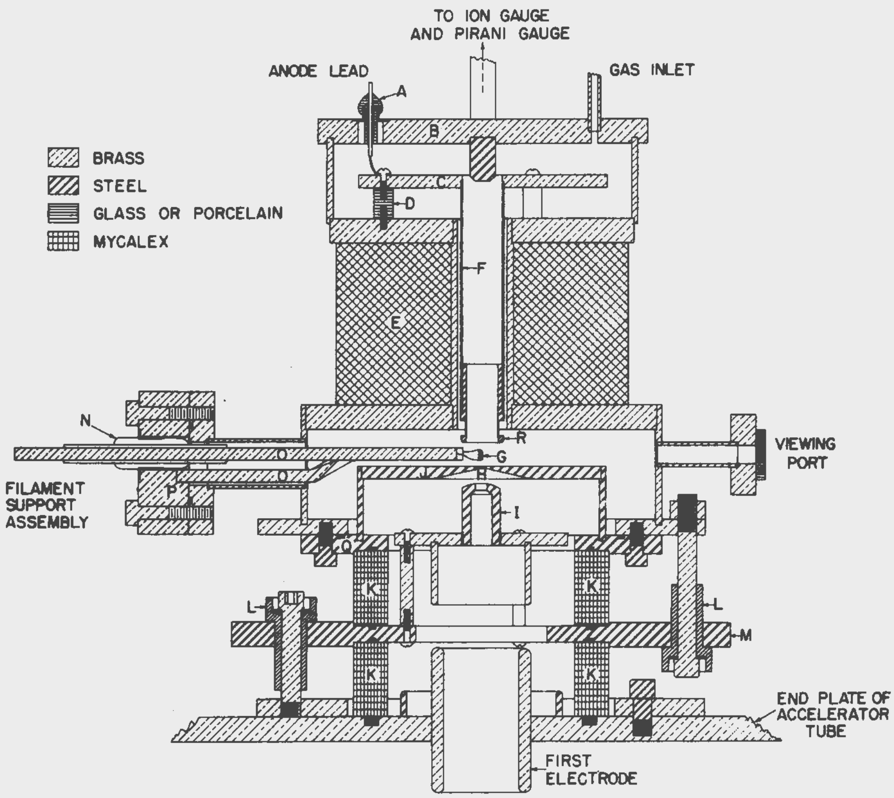
TO ION GAUGE
AND PIRANI GAUGE
ANODE LEAD
GAS INLET
BRASS
STEEL
GLASS OR PORCELAIN
MYCALEX
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
FILAMENT
SUPPORT
ASSEMBLY
VIEWING
PORT
END PLATE OF
ACCELERATOR
TUBE
FIRST
ELECTRODE

FIGURE I

IV. PERFORMANCE

The ion source was tested on the accelerator tube of the kevatron using hydrogen gas. The anode voltage, anode current, filament current, magnet current, probe voltage, probe current, first electrode voltage, and ion source pressure could be read at all times. The first tests were made by shorting together all but the first electrode of the accelerator tube and then using the lower part of the tube to collect the ion current. The ion source pressure was read on a type 35T ionization gauge which was approximately calibrated for hydrogen gas. During these tests the first electrode voltage was adjusted so that all the ions passing through the probe would be focused into the lower part of the accelerator tube and read as ion current.

The two different types of filaments previously described were tried in the ion source at various spacings from the exit hole. It was concluded from the results of these tests that a 20 mil tungsten filament in the form of a $2\frac{1}{2}$ turn helix was preferable to a flat spiral filament. The reasons for this preference were as follows:

1. It was possible to obtain larger ion currents with the helix filaments.

2. The helix filaments were easier to make and easier to mount in the ion source.

3. The helix filaments appeared to have a longer lifetime. The lifetimes varied from 50 hours to more than 100 hours and depended on the operating conditions of the ion source.

A 60 cycle modulation of the beam was observed, and its amplitude was found to vary with the operating conditions of the ion source. When the filament was heated with direct current the 60 cycle modulation was observed to be reduced but still varied with ion source conditions and, thus, the comparison was not considered to be conclusive as to the origin of the modulations.

The anode extension was varied in order to determine if it had an optimum position. The largest ion current was obtained when the end of the anode was $\frac{1}{2}$ in. from the bottom plate.

Using a helix filament heated with a.c. current, an anode-to-bottom plate spacing of $\frac{1}{2}$ inch, and hydrogen gas, a careful analysis was made of the dependence of the total ion current upon the operating conditions of the ion source. The data recorded illustrated the following operating characteristics:

1. Pressure

The ion source was operated in the pressure range of 1 to 2.5 microns of Hg while the probe voltage, filament current, and magnet current were held constant. For each pressure the anode voltage was adjusted to give a maximum ion output. For these conditions the dependence of the ion current on pressure is illustrated in Figure 2. The total ion current increased with pressure to a maximum at 2 microns and then decreased slightly thereafter. For pressures below 1.5 microns the discharge became unstable. This pressure dependence and range differ considerably from the values reported by Kistemaker and Dekker but agree more favorably with Cornelius and Farwell's report of a range of 1 to 2 microns for stable operation.

2. Magnet Current

The magnet coil current was varied from 0 to 10 amperes while probe voltage, filament current, and ion source pressure were held constant. The anode voltage was adjusted to give a maximum ion current for each value of magnet current. As illustrated in Figure 3 a minimum magnet current of 3 amperes was required to maintain stable operation. The ion current increased to a maximum at about 5 amperes which corresponds to a field intensity at the end of the anode of about 175 oersteds. This perhaps indicates that for magnet current of 5 amperes or larger all the primary electrons from the filament are passing through the anode. For magnet currents larger than 5 amperes the ion current actually appeared to decrease slightly.

3. Anode Voltage

The probe voltage, magnet current, filament current, and the ion source pressure were held constant while the total ion current, the anode current, and the probe current were measured for various anode voltages. For the particular pressures used, the ion current had a definite maximum at an anode voltage of 110 volts as illustrated in Figure 4. At lower anode voltages the ion current was approximately proportional to it except at very low voltages where the discharge became unstable. At voltages above 110 volts the current to the probe increased rapidly and the ion current decreased. This perhaps can be explained by the hypothesis that as the anode voltage is increased the ions become more strongly focused toward the exit hole, hence, are very diverging as they approach the probe and, consequently, strike it. Thus, although more ions are focused to the exit hole and more are extracted, fewer are accelerated past the probe. The current to the probe was not all ion current but in part due to secondary electrons from the probe.

The curves of Figure 4 were displaced considerably by changing either the spacing between the anode extension and the bottom plate or by changing the position of the filament relative to the anode. Ion currents as large as 5 ma were obtained under

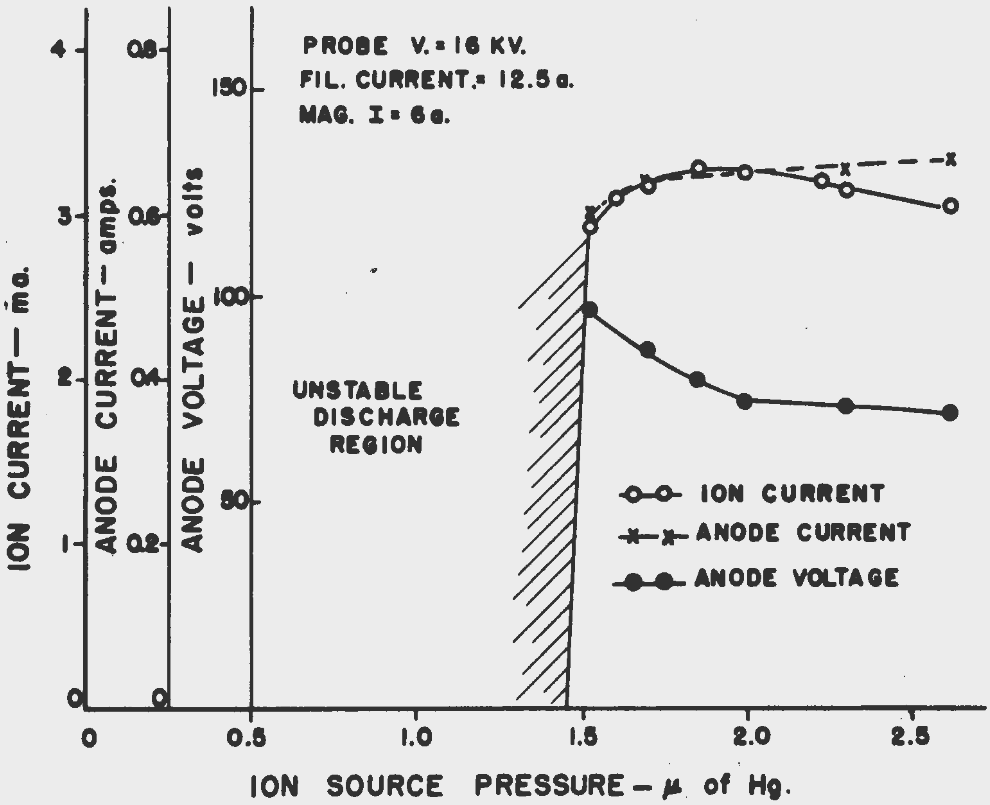
PROBE V. = 16 KV.
FIL. CURRENT = 12.5 a.
MAG. I = 6 a.
ION CURRENT — ma.
ANODE CURRENT — amps.
ANODE VOLTAGE — volts
UNSTABLE DISCHARGE REGION
ION CURRENT
ANODE CURRENT
ANODE VOLTAGE
ION SOURCE PRESSURE — μ of Hg.

FIGURE 2

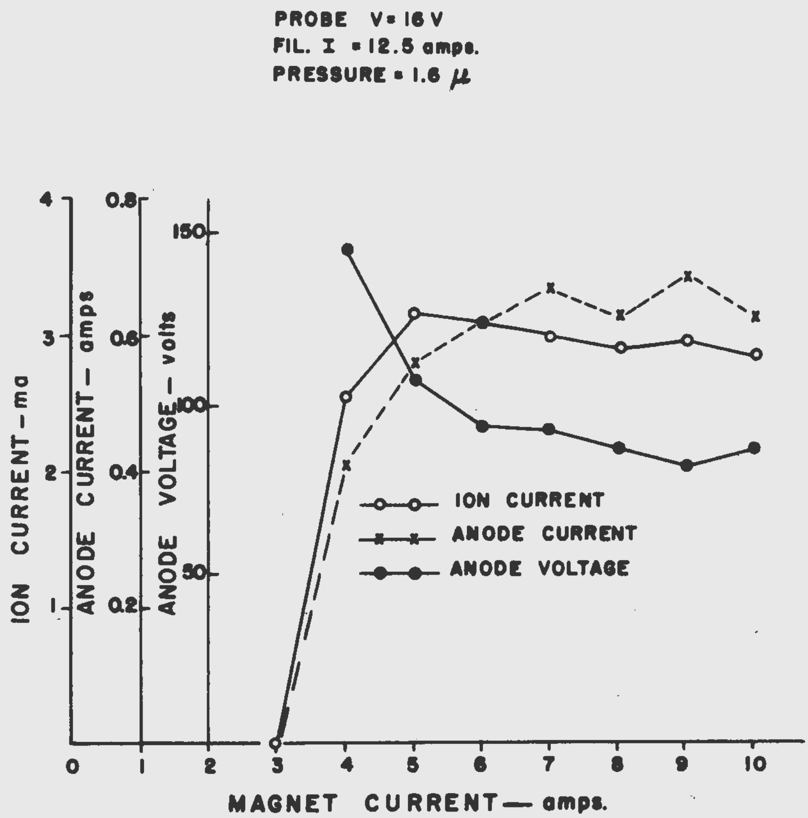
PROBE V = 16 V
FIL. I = 12.5 amps.
PRESSURE = 1.6 μ
ION CURRENT - ma
ANODE CURRENT - amps
ANODE VOLTAGE - volts
ION CURRENT
ANODE CURRENT
ANODE VOLTAGE
MAGNET CURRENT — amps.

FIGURE 3

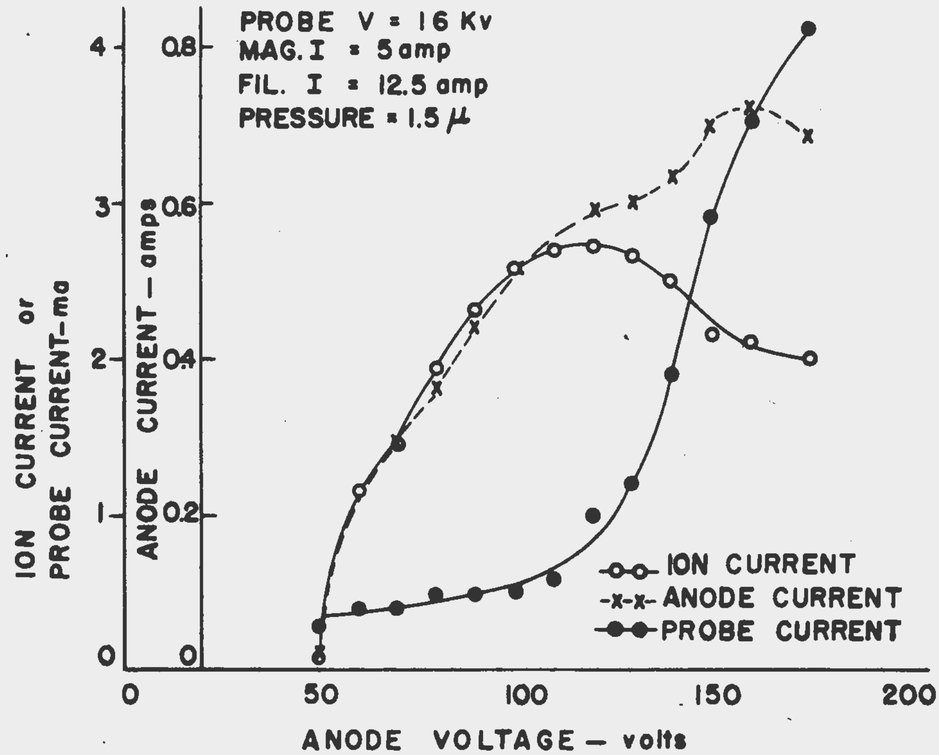
PROBE V = 16 Kv
MAG. I = 5 amp
FIL. I = 12.5 amp
PRESSURE = 1.5 μ
ION CURRENT or PROBE CURRENT-ma
ANODE CURRENT — amps
ION CURRENT
ANODE CURRENT
PROBE CURRENT
ANODE VOLTAGE — volts

FIGURE 4

some conditions.

4. Filament Current

Earlier tests on the ion source had indicated an unexpected dependence of the ion output on the filament emission. Figure 5 illustrates this dependence as a function of filament current for constant probe voltage, magnet current, and ion source pressure. Again the anode voltage was adjusted to give a maximum ion current for each filament current. The ion output increased with filament current to a maximum at 12.5 amperes and then decreased for larger filament current. Perhaps this decrease in ion current is due to neutralization of the ions by the electronic space charge about the filament.

5. Probe Voltage

For a constant ion source pressure, filament current, magnet current, and anode voltage the ion current was measured as the probe voltage was varied. The results are illustrated in Figure 6. At very low voltages nearly all the ions were striking the probe, and hence, there was very little ion current. The ion current actually read negative due to secondary electrons from the probe. As the probe voltage was increased the ion current increased to saturation at about 16 kv. It is difficult to draw any conclusions from these data since the number of secondary electrons coming off of the probe and the number collected with the ion current were unknown. In general, after the saturation point for the ion current is reached, an additional increase in ion current could be achieved by increasing the anode voltage.

Additional tests were made by applying the high voltage (10 to 300 kv) to the accelerating tube.

6. Focusing

The focusing was adjusted by varying the voltage on the first electrode of the accelerator tube (0 to 10 kv with respect to the ion source case). The focusing conditions and the degree of focusing which could be obtained were found to be very dependent on both the beam intensity and the accelerating voltage. The best focus obtained for a 3 ma beam at 300 kv on a target about 2 meters from the ion source was a beam diameter of about 5 mm. This could probably be improved by making the exit hole smaller. As the accelerating voltage was decreased below 150 kv, it was necessary to decrease the beam intensity in order to maintain good focusing. Presumably this was due to space charge effects in the beam. In the region below 20 kv it was difficult to focus beams larger than $\frac{1}{2}$ ma to a diameter of less than 3 cm at the target.

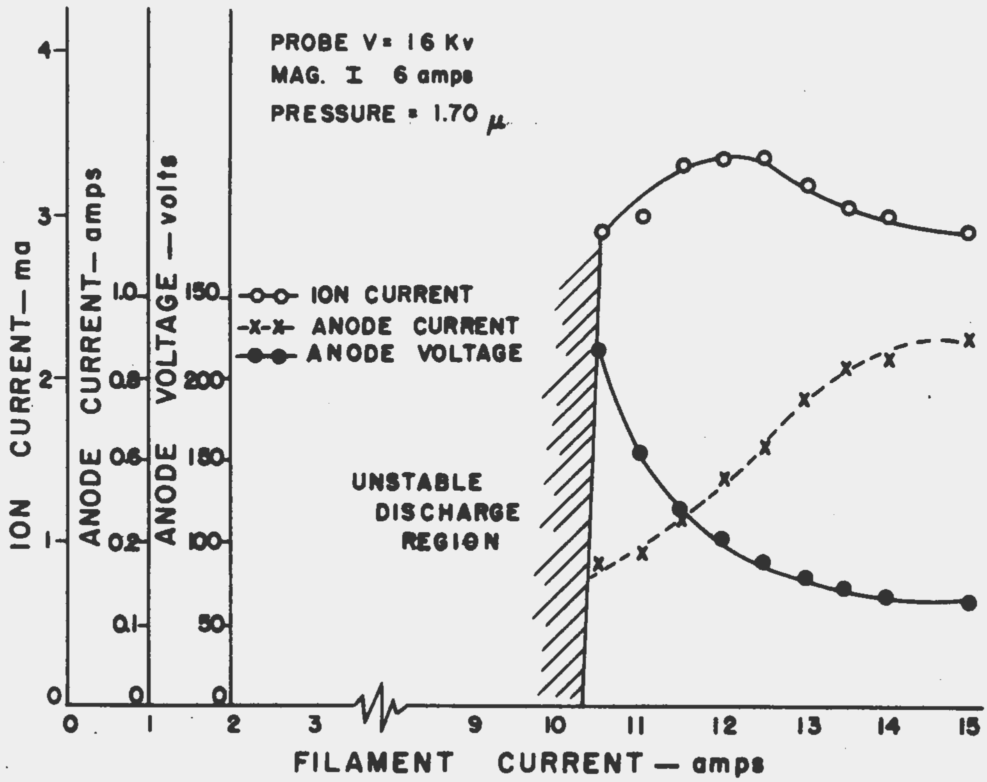
PROBE V = 16 Kv
MAG. I 6 amps
PRESSURE = 1.70 μ
ION CURRENT — ma
ANODE CURRENT — amps
ANODE VOLTAGE — volts
ION CURRENT
ANODE CURRENT
ANODE VOLTAGE
UNSTABLE DISCHARGE REGION
FILAMENT CURRENT — amps

FIGURE 5

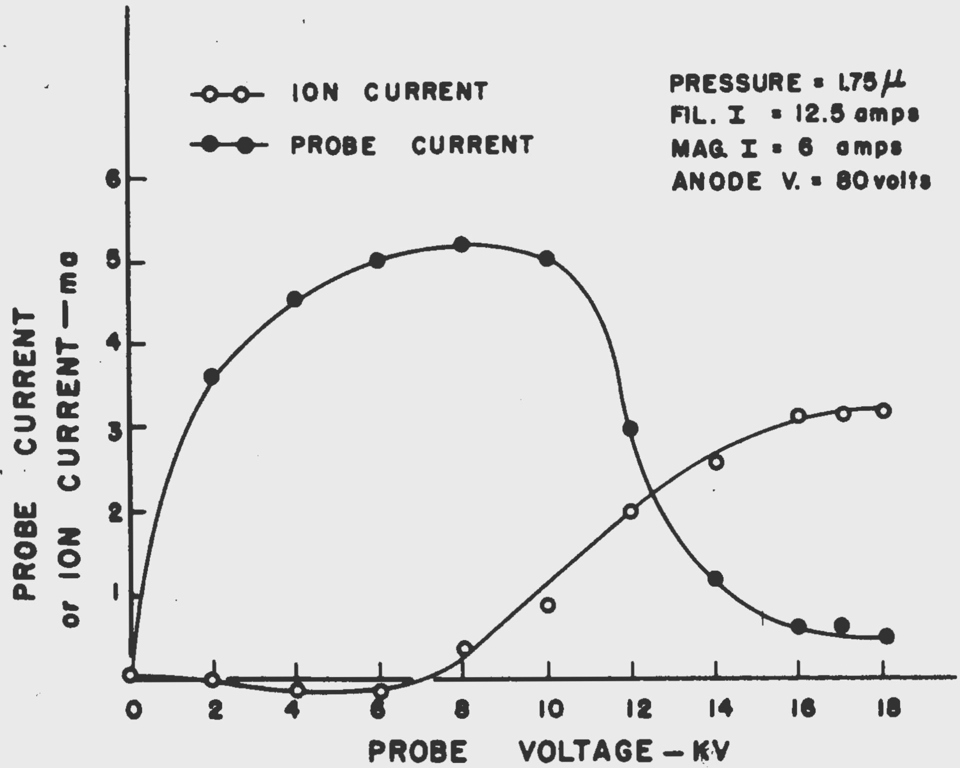
ION CURRENT
PROBE CURRENT
PRESSURE = 1.75 μ
FIL. I = 12.5 amps
MAG. I = 6 amps
ANODE V. = 80 volts
PROBE CURRENT or ION CURRENT — ma
6
5
4
3
2
1
0
2
4
6
8
10
12
14
16
18
PROBE VOLTAGE — KV

FIGURE 6

7. Proton Percentage

The ion beam composition was studied with a magnetic analyzer. The proton percentage was measured for several ion source conditions and was found to vary over the range of 5 to 10%. The ion source conditions for a particular measurement were as follows:

Filament current	12.5	amperes
Magnet current	6.0	amperes
Ion source pressure	1.9	microns
Probe voltage	7.0	kv
Probe current	2.5	ma
First electrode voltage	4.0	kv
Anode voltage	70.	volts
Anode current	0.42	amperes
Total beam current	300	ua

The components of the ion beam were identified as follows:

Component	Collector Current-ua	% of Total Current
Protons H^+	1.7	8.3%
Diatomic ions H_2^+	13.9	67.8%
Triatomic ions H_3^+	4.5	21.9%
Misc. heavy ions	0.4	

The remainder of the ion current was lost to the slits of the magnetic analyzer. Although the above ion source conditions were considerably different from those required to produce total beam currents of 2 to 3 ma, the results of the analysis were typical for the pressure and magnet current used.

8. Gas Consumption

A palladium leak was used to admit the hydrogen gas into the ion source. When the ion source was not operating but a pressure of 1.75 microns was maintained in it the gas flow was measured to be 20.5 ± 3.4 cc/hr, STP. The gas consumption when the ion source was operating at a pressure of 1.75 microns and with a 2.5 ma beam was measured to be 22.5 ± 2.8 cc/hr, STP. A 2.5 ma beam of diatomic ions was calculated to be equivalent to a gas flow of 2.09 cc/hr, STP. Kistemaker and Dekker defined a gas economy figure as the number of ions extracted from the source per neutral gas molecule escaping through the exit hole. Accordingly, our figure would be 10.2% compared with Kistemaker and Dekker's value of 50%. Our low gas economy figure was in part due to the large exit hole used during these measurements. In earlier tests the exit hole was 0.06 in. in diameter but was enlarged to 0.12 in. in diameter in an effort to increase the ion output. However, this change did not significantly increase the maximum ion current; thus, it could just as well be made smaller again. Also, our ion source operated at a considerably higher pressure than that reported by Kistemaker and Dekker.

9. Power Consumption

Anode	50 watts
Anode ballast	50 watts
Filament	25 watts
Magnet	60 watts
Pd leak	9 watts
Probe	16 watts
First electrode	10 watts
Total	221 watts
Misc. power to power supplies and blowers	250 watts

The top plate and magnet of the ion source were cooled with a blower. No difficulty with overheating was encountered.

V. SUMMARY AND DISCUSSION

The performance of the Kistemaker and Dekker type ion source described above has been stable and reliable while operating at pressures of 1.5 to 2.5 microns and producing ion currents of 3 ma. Its gas consumption is relatively high (22.5 cc/hr, STP) but could be reduced by using a smaller exit hole. The proton percentage is extremely low (the order of 8%), but this could possibly be improved some by coating the metal surfaces which are exposed to the discharge with a suitable material to reduce the recombination of the H atoms. The best focusing gave a beam diameter of 5 mm on a target 2 meters from the ion source. It is felt that the focusing could be improved by redesigning the shape of probe and by decreasing the size of the exit hole. The filaments have had lifetimes of from 50 to more than 100 hours which has been satisfactory for our work considering the ease with which the filament can be replaced. By varying the anode and filament dimensions and increasing the power to the discharge, ion currents as large as 5 ma were obtained, and perhaps by further adjustment of these parameters even larger ion currents could be obtained. This would probably shorten the lifetime of the filament considerably. The power consumption for beams of 3 ma or less was found to be about 0.15 watts/ua.

The chief disadvantage of this ion source for our work is its low proton percentage. It is felt that considerable effort would be required to increase the proton ratio significantly and its upper limit would be of the order of 50%. Recent reports on the development of R.F. ion sources (7,8,13, 14) have led us to the opinion that future work can be more profitably applied to the construction of an R.F. type ion source. Consequently, the design and plans for construction of such an ion source have been started.

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